

Draft Report for Information

**NRC Fire Risk Research Plan: Fiscal Years 1998-2000**

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## **ABSTRACT**

The U.S. Nuclear Regulatory Commission (NRC) has initiated a research program aimed at addressing gaps in current capabilities to perform realistic fire risk assessment. The intent of the program is to support an expanded use of risk-informed, performance-based methods for fire protection applications. This report summarizes the current research plan for the program, including the program objectives, summary task descriptions, a summary of the overall program schedule, and potential future activities. References are also provided for readers interested in additional details on fire risk assessment, fire research, and NRC's plans.

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## 1. BACKGROUND

As stated in the U.S. Nuclear Regulatory Commission's (NRC's) policy statement on the use of Probabilistic Risk Assessment (PRA) [1], the NRC intends to increase the use of PRA technology in "all regulatory matters to the extent supported by the state of the art in PRA methods and data." Recent activities include the development of a general risk-informed<sup>1</sup> framework for supporting licensee requests for changes to a plant's licensing basis, described in Regulatory Guide (RG) 1.174 [3]; and efforts to make Part 50 of the Code of Federal Regulations more risk-informed.

In the area of fire protection, there is interest from both the NRC and industry in the use of PRA technology to deal with outstanding issues (see, for example, Refs. 4-8). Specific applications include the identification of plant-specific vulnerabilities, the evaluation of the acceptability of proposed changes to specific parts of a plant's program, the evaluation of the safety significance of certain fire protection issues (e.g., fire-induced circuit failures), and the evaluation of the safety significance of fire protection inspection findings. An industry consensus standard (NFPA 805) which uses risk information in evaluating a plant's fire protection program, is being developed under the auspices of the National Fire Protection Association (NFPA) [9]. It is anticipated that the completed standard will use an approach that is compatible with RG 1.174.

When used in a risk-informed decision making framework, fire risk assessment (FRA) is useful in that it provides a systematic, integrated method for evaluating the importance of fire protection issues. However, the current FRA state of the art is not as mature as that for assessing the risk contributions of many other important accident initiators. As shown by a recent review of Individual Plant Examinations of External Events (IPEEEs) [10], variations in analytical assumptions can lead to orders of magnitude variation in estimates of fire-induced core damage frequency (CDF), and qualitatively different risk insights are possible. Such uncertainties can clearly affect a decision maker's confidence in the results of FRAs and lead to, in hindsight, suboptimal decisions.

SECY-98-230 [11] identifies a number of areas where improvements in FRA methods, tools, and data will improve the ability of FRA to support decision making. A more detailed discussion of these areas and the process used to identify them is presented in Ref. 12. To address these areas, the Office of Nuclear Regulatory Research (RES) initiated a fire risk research program in Fiscal Year (FY) 1998.

This report documents the current research plan for the RES fire risk research program. The report is intended to provide information to readers interested in the technical basis for the tasks being pursued, as well as readers interested in programmatic issues (e.g., scheduling, and task and program interactions). It covers the program objectives (Section 2), the individual task descriptions (Section 3), relevant fire protection activities (including both NRC and non-

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<sup>1</sup>Ref. 2 defines a risk-informed approach as follows: "A risk-informed approach to regulatory decision making represents a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to public health and safety."

NRC programs) interacting with the program (Section 4), the overall schedule (Section 5), and potential future activities (Section 6). A list of references is provided at the end of the report. The report's appendices show how the program addresses previously identified fire protection issues (Appendix A) and fire risk research issues (Appendix B).

## 2. PROGRAM OBJECTIVES AND CHARACTERISTICS

### 2.1 Program Objectives

The general objectives of the fire risk research program are consistent with those of the Office of Nuclear Regulatory Research.<sup>2</sup> They are as follows.

Improve qualitative and quantitative understanding of the risk contribution due to fires in nuclear power plants.

- ! Support ongoing or anticipated fire protection activities in the NRC program offices (especially the Office of Nuclear Reactor Regulation), including the development of risk-informed, performance-based approaches to fire protection.
- ! Develop improved fire risk assessment methods and tools (as needed to support the preceding objectives).

The technical objectives of the program are largely focused on the three elements of fire protection defense in depth (fire prevention, fire detection and suppression, fire mitigation). (This is because current methods for performing fire risk assessment (FRA) are structured in a similar fashion.<sup>3</sup>) They are, for the most part, aimed at developing an FRA state of the art which is, loosely speaking, comparable in quality to that for current PRA for other internal events. In particular, they are aimed at developing:

- ! improved estimates of the frequencies of challenging fires;
- ! improved fire modeling tools for risk significant scenarios, including guidance for proper application (accounting for limitations and uncertainties);
- ! mode-specific thermal fragilities for cables and other key components;

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<sup>2</sup>The RES objective directly addressed by this research program is the development and use of risk information and insights to improve regulatory effectiveness. The program also supports a number of other RES objectives, including: the development of technical bases to address identified or potential safety issues, the improvement of program efficiency (through the support of consensus standards development), the determination of the regulatory significance of new technical information, and the development of technical bases to allow reductions to unnecessary licensee burden.

<sup>3</sup>In a typical FRA, the CDF contribution due to a given fire scenario (where a fire scenario is defined by the location and burning characteristics of the initiating fire) can be decomposed into three components: the frequency of the fire scenario, the conditional probability of fire-induced damage to critical equipment given the fire, and the conditional probability of core damage given the specified equipment damage. Detailed descriptions of the general FRA methodology are provided in a number of references (see, for example, Refs. 13-16).



- ! guidance for identifying scenarios for which smoke effects may be risk significant;
- ! improved estimates of the probability of fire and fire effects containment (including active and passive barriers);
- ! configuration- and condition-sensitive fire protection system reliability estimates, including guidance for application;
- ! improved tools for assessing the risk impact of circuit interactions; and
- ! improved understanding of the implications of major fire events for FRA.

## 2.2 Program Elements

Figure 1 illustrates the general features of the fire risk research program. The program includes elements for: problem identification and prioritization (based upon the program input on the left hand side of the figure), information development and technical analysis, tool development, results communication (output), and program management (including the incorporation of feedback<sup>4</sup>).

## 2.3 Program Philosophy

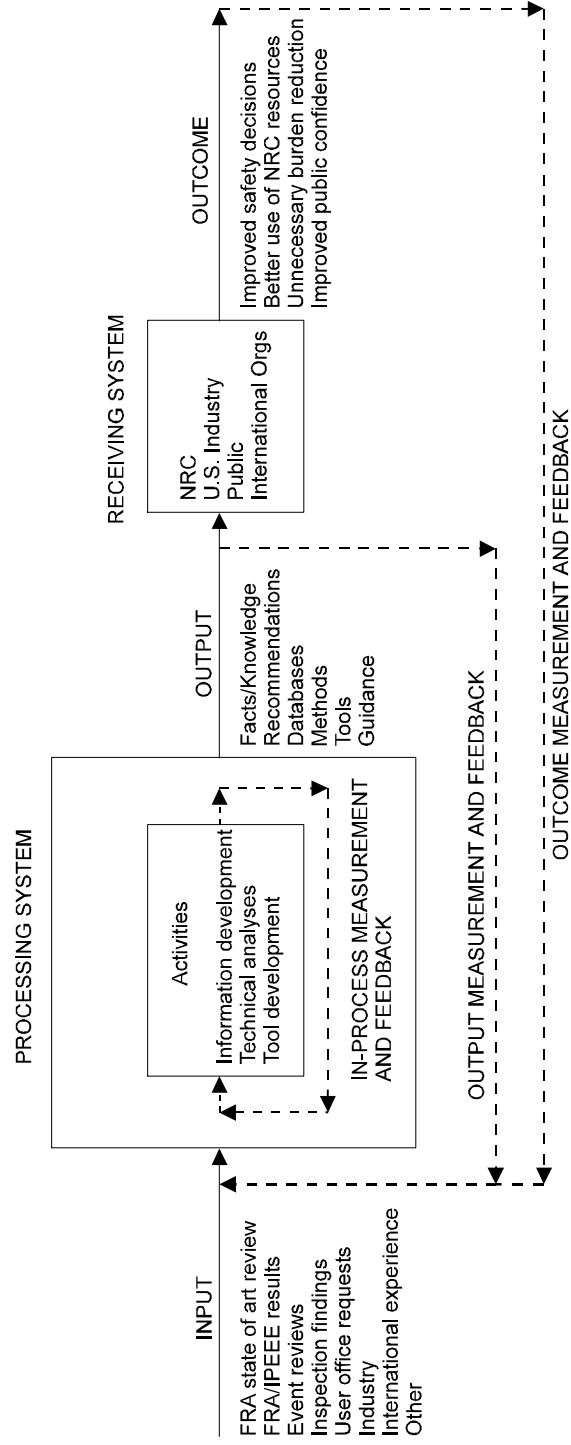
The program has been designed based on a recognition that: a) the desired improvements in FRA methods, tools, and data should lead to a state of the art comparable to that for internal events PRA; and b) resources for improving FRA are limited. Consequently, the program focuses on the development of evolutionary improvements on existing FRA approaches, or even improved guidance for using these approaches, as opposed to the development of new methodologies. It emphasizes the improved use of existing information, and generally avoids the performance of new experiments. In cases where the technical issues cannot be adequately dealt with using these approaches, the program employs feasibility or scoping studies to support planning for more detailed studies.

The program also takes into account ongoing, parallel activities. In the case of other research programs (e.g., the RES ATHEANA program, which is developing an improved method for human reliability analysis [17]), the fire risk research program is designed to use the results of these efforts when they become available. In the case of key activities (e.g., the NFPA 805 standard development) which can benefit from its results, the fire risk research program is designed to generate products to support these activities as much as possible. These program interactions are further discussed in Section 4.

It is recognized that the NRC has interests in fire issues that are not necessarily fire risk related. Per the discussion in SECY-98-230, these issues are not covered by the fire risk research program; the NRC staff will seek Commission approval before initiating research on these issues.

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<sup>4</sup>Recognizing the difficulty in unambiguously linking decision outcomes to program outputs, especially since risk-informed decisions are not based entirely on risk [2], it is anticipated that the program's performance assessment and associated modifications will be primarily based on the program outputs.



Adapted from: National Research Council, "World-Class Research and Development: Characteristics for an Army Research, Development and Engineering Organization," National Academy Press, Washington, D.C., 1996, ISBN 0-309-05589-X.

Figure 1. Schematic of Fire Risk Research Program

### 3. TASK DESCRIPTIONS

The technical tasks included in the fire risk research program are listed in Table 1. This section provides, for each task, a description of the background for the problem being addressed; the task technical scope; the technical objectives; the task schedule and lead; and the task outputs and interactions with other tasks and other fire protection activities. The tasks are ordered by the organization having the technical lead.

#### 3.1 Tools for Circuit Failure Mode and Likelihood Analysis

##### 3.1.1 Background

Besides determining the likelihood of equipment failure, an FRA needs to specify the failure mode, i.e., how the failure occurs. Of particular interest when dealing with fire-induced damage to electrical cables are the loss of function or spurious actuation of equipment associated with the cables. In FRAs, the latter failure mode is typically assumed to be caused by "hot shorts," i.e., short circuits involving a powered conductor.

Hot shorts can result in the application of power to unpowered circuits, the application of destructive voltages to lower power-voltage circuits, false instrument readings, or the simulation of a switch closing. In turn, these effects can lead to spurious operation of plant equipment (e.g., valves and pumps), damage to that equipment, and erroneous plant process monitoring indications that adversely impact the ability to achieve safe shutdown following a fire. Hot shorts are addressed by current NRC fire protection regulations and guidance documents. (See Appendix R Section III.G.2, GL 86-10 Section 5.3, IN 87-50, and IN 92-18.)

Hot shorts can be a significant direct and indirect risk contributor. In one advanced reactor design FRA, hot short scenarios (leading to medium or large LOCAs due to spurious valve operation) contribute over 95% of the fire-induced CDF for that design. A recent inspection at a boiling water reactor plant has shown that a single hot short can lead to an unisolable opening of all 16 safety relief valves. Complications in procedures designed to address the potential of equipment damage due to hot shorts contribute to the significant fire risk contribution at another boiling water reactor plant.

From a risk assessment standpoint, a major concern is that hot short analyses performed for FRAs are generally simplistic. The probability of a single hot short is commonly based on a generic probability distribution derived subjectively in Ref. 18 from a limited amount of information. (The distribution, assumed to be lognormal, has a 5th percentile of 0.01 and a 95th percentile of 0.20; its mean value is 0.07.) The probability of multiple hot shorts is typically obtained by multiplying this probability an appropriate number of times. The latter procedure ignores the potentially significant impact of dependencies, both aleatory and epistemic. Furthermore, both it and the original single hot short distribution do not explicitly reflect such potentially important issues as the circuit design, the function of the cable, and the characteristics of other cables in the vicinity.

A second concern is that FRAs do not address the full set of effects that may result from a fire-induced circuit fault (e.g., the simulated closure of a switch). FRAs deal with the loss or spurious actuation of equipment caused by damage to the cable servicing the equipment. They usually do not propagate the electrical faults caused by the cable damage

through the affected electrical circuit(s) to determine if additional faults (or even fires) occur. If such a propagation is done, it is not done probabilistically.

### 3.1.2 Task Scope

Recognizing that the specific response of a circuit to fire-induced cable damage will vary with circuit design, the focus of this task is on the development of input needed to perform a probabilistic systems analysis. Thus, for example, the task results are intended to enable the estimation of the probability of fire-induced circuit faults (e.g., application of power to an unpowered circuit). Only a limited set of simplified, scoping calculations involving the propagation of faults through sample circuits will be performed to indicate the potential risk significance of the task results.

This task represents the first phase of a detailed study of the issue. The results of this analysis will be used to determine where additional work (possibly including experiments) are needed.

### 3.1.3 Task Objectives

- ! To develop an improved understanding of the mechanisms linking fire-induced cable damage to potentially risk significant failure modes of power, control, and instrumentation circuits.
- ! To develop improved methods and data for estimating the conditional probabilities of key circuit faults, given damage to one or more cables.
- ! To develop sample estimates of the conditional probabilities of key circuit failure modes applicable to currently operating U.S. nuclear power plants. The estimation process will include an identification and quantification of the key uncertainties in the estimates.
- ! To gain risk insights concerning fire-induced circuit failures, especially those associated with cable hot shorts.
- ! To identify areas where additional work needs to be done to improve understanding of the risk associated with fire-induced circuit failures.

### 3.1.4 Schedule and Lead

Start Date	July 1998
Completion Date	The draft final letter report is due September 30, 1999.
Lead	J. LaChance, Sandia National Laboratories (SNL)

### 3.1.5 Outputs and Interactions

The principle outputs of this task are the identification of important factors affecting the likelihood of different fire-induced circuit failure modes, improved methods and data for

estimating the probabilities of these failure modes, and the identification of additional work needed (if any) to improve understanding of the risk associated with these failures.

The results of this task are expected to support ongoing NRC/industry activities concerning the resolution of the fire-induced circuit failure fire protection issue [5,8], and the development of the circuit analysis and FRA portions of NFPA 805.

### 3.2 Tools for Fire Detection and Suppression Analysis

#### 3.2.1 Background

Within the context of FRA, the objective of a detection and suppression analysis is to determine the likelihood that a fire will be detected and suppressed before the fire can damage critical equipment. This requires, among other things, an assessment of the performance of automatic suppression systems and of the effectiveness of manual fire fighting efforts.

A variety of methodologies for performing this analysis have been used in FRAs. Refs. 19 and 20 describe a methodology which assesses the likelihood of various detection/suppression scenarios and their associated suppression times using generic fire protection system reliability estimates and detection/suppression time data obtained from nuclear power plant fire events; Ref. 21 describes an application of this methodology. The detection/suppression model used by this methodology is sufficiently broad to cover models used by other methodologies, e.g., the LaSalle FRA [22], the Electric Power Research Institute's (EPRI's) Fire-Induced Vulnerability Evaluation (FIVE) [23], and the EPRI Fire PRA Implementation Guide [16].

Regardless of the methodology employed, fire suppression analyses require estimates of the reliability of automatic suppression systems.<sup>5</sup> Some weaknesses in current FRA practices regarding these estimates are as follows. First, current FRAs use generic non-nuclear industry estimates for system unreliability. Aside from questions concerning their universal applicability to nuclear power plant (NPP) situations (NPP installations are not always performed according to current codes and standards), these estimates can account for plant-to-plant variability in only an average manner. For example, the estimates for an automatic sprinkler system cannot account for variations in such plant- and scenario-specific factors as sprinkler head location relative to the fire, sprinkler system design, room congestion, and the behavior of the fire. Second, the suppression system reliability estimates are generally based upon data for system actuation; they do not address the issue of suppression system effectiveness, i.e., the conditional probability of suppression, given actuation. One consequence is that the use of generic suppression system reliability estimates may be

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<sup>5</sup>Note that the system reliability at time  $t$ ,  $R(t)$ , is mathematically defined as the probability that system failure occurs after  $t$ . The definition of "failure" is determined by the particulars of the problem.

optimistic in studies where severity factors<sup>6</sup> are used in the fire initiation analysis. This is because the reliability estimates are not conditioned on the fire severity.

From the definition of fire protection system reliability, it can be seen that a suppression analysis also requires estimates of the delay times (e.g., the time to initiate fire suppression, the time to final suppression) characteristic of the fire suppression process. More precisely, since these times should be modeled as random variables, estimates of the parameters of the aleatory distributions for these times are required. Currently available methods for estimating these parameters involve the use of empirical event data (e.g., [16,19,20]), simple physical models (e.g., [23]), or expert judgment (e.g., [22]).

Regarding event data, one key concern is the limited amount of data underlying current delay time parameter estimates. The distributions reported in Refs. 19 and 20 are based on data collected in the early 1980's and may not reflect recent nuclear power plant experience. While more recent studies have a more complete set of data, they do not address all of the characteristic delay times identified in Ref. 19. A second concern is the ability of a statistical approach to address the effects of such factors as the location, severity, and accessibility of the fire; the available data from plant fire events are generally insufficient to quantify these effects.

In principle, model-based approaches can be used to specialize event-based generic distributions to account for scenario-specific features. However, it is not clear how this specialization should be done, especially in light of the recognized uncertainties in currently available models for predicting smoke and temperature levels in realistic power plant scenarios. It is important to observe that fire models which are conservative with respect to fire damage predictions may be non-conservative with respect to fire suppression.

Expert judgment provides another way to account for plant-specific features. Supported by the results of plant fire brigade drills, it has been used in many FRAs to estimate the time to manual suppression. The analyses typically assume that the manual suppression time equals the brigade arrival time and often do not account for delays associated with detection (prior to brigade activation) or actual fire suppression (following brigade arrival). They also typically do not address aleatory uncertainties associated with the suppression process, e.g., variations in response time due to the time of day. The LaSalle FRA [22] addresses these concerns to some extent by using expert judgment to estimate the minimum, maximum and average times to detection, suppressant application, and suppression (or substantial control) for a variety of scenarios. However, the LaSalle FRA has the same basic problem as other FRAs using expert judgment in the detection and suppression analysis - it has not integrated the results of the expert elicitation process with actual data.

The preceding discussion addresses estimation issues in suppression analysis. Modeling issues which are not quantitatively addressed by most FRAs include: the impact of smoke and loss of lighting on the effectiveness of manual fire fighting and the effectiveness of compensatory measures (e.g., fire watches) for temporary fire protection deficiencies. The first

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<sup>6</sup> "Severity factors" (see Section 3.10) are commonly used in FRAs to model the fraction of reported fires that have the potential to cause damage to components not involved in the initial fire.

issue includes the possibility of misdirected suppression efforts which can damage sensitive plant equipment. Some but not all of the information needed to address this issue is presented in Refs. 22 and 24. The first issue also includes the possibility that scenario-specific smoke and loss of lighting effects will require modifications to the generic suppression time distributions used in many FRAs. The second issue stems from the observation that a number of FRAs assume that fire watches are as reliable as automatic systems in suppressing fires regardless of the fire characteristics. There currently is no technical basis to confirm or refute this assumption.

The general modeling framework described in Ref. 19 appears to be sufficiently broad and detailed to incorporate treatments of the issues discussed above. However, updates in the model parameter estimates are needed. Furthermore, improvements are needed to integrate potentially useful other forms of information (e.g., the predictions of physical models for detection and suppression, the results of fire brigade drills).

### 3.2.2 Task Scope

This task is not aimed at dealing with detailed fire growth and suppression interactions (e.g., reductions in fire suppression effectiveness as the fire grows; retardation of fire growth by initial applications of suppressants). If these must be treated (e.g., in non-FRA applications), a more simulation-based approach for modeling suppression will be needed.

### 3.2.3 Task Objectives

- ! To develop improved methods and data for estimating the reliabilities of automatic and manual suppression activities.
- ! To develop estimates of these conditional probabilities applicable to currently operating U.S. nuclear power plants.
- ! To identify and quantify key uncertainties in these estimates.

### 3.2.4 Schedule and Lead

Start Date	April 1999
Completion Date	The draft final letter report is due June 30, 2000.
Lead	M. Kazarians, Kazarians and Associates.

### 3.2.5 Outputs and Interactions

The principle outputs of this task follow from the task objectives: improved methods and data for estimating the reliabilities of suppression activities; estimates of these reliabilities; and an evaluation of the uncertainties in these estimates.

This task will use non-nuclear fire information generated by the task "Industrial Fire Experience" (see Section 3.6). This task is also expected to interact with the task "Fire Barrier Reliability Model Development and Application" (see Section 3.8).

The results of this task will be useful to potential future NRC/industry activities concerning the application of FRA in the resolution of fire protection issues (including, for example, the evaluation of compensatory measures).

### 3.3 IEEE-383 Rated Cable Fire Frequency Analysis: Feasibility Study

#### 3.3.1 Background

One key issue in fire frequency analysis for FRA concerns the frequency of self-ignited fires involving IEEE-383 rated cables. Tests have shown that electrical ignition of fires involving these cables is difficult (e.g., see Ref. 25). A practical FRA question is, for compartments containing only rated cables, what is the frequency of cable fires? Is it sufficiently low that the analysis only need consider transient-fueled fires? As shown by the results of a number of IPEEEs, differences in analysis assumptions can lead to qualitatively different risk insights.

Nuclear power plant data for self-ignited cable fires are sparse; the number of reported events is small and the event descriptions rarely include much detail about the types of cables involved. Thus, answers to the above questions will probably require: a) a broadening of the database to include events occurring in other facilities and industries, and b) models of potential fire initiation scenarios which address the influence of key phenomenology.

#### 3.3.2 Task Scope

This task involves a feasibility study which represents the first of two project phases. Depending on the results of the first phase, a follow-on task may be needed for the second project phase (which covers actual methodology development and analysis).

#### 3.3.3 Task Objectives

- ! Determine if there is an adequate technical basis for asserting that the frequency of self-ignited fires involving IEEE-383 rated cables is too small to consider in nuclear power plant FRAs.
- ! Failing the above, determine the feasibility of developing a practical, improved methodology for estimating the frequency of such fires.
- ! Identify the work needed to develop and implement this methodology.

#### 3.3.4 Schedule and Lead

Start Date	February, 1999
Completion Date	The draft final letter report is due August 30, 2000.
Lead	S. Nowlen, SNL



### 3.3.5 Outputs and Interactions

The principle outputs of this task are assessments of: a) the current technical basis for estimating the frequency of self-ignited fires involving IEEE-383 rated cables, and b) the feasibility of developing improved estimates.

This task will use cable flammability information collected under the task “Fire Modeling Toolbox: Input Data and Assessment” (see Section 3.4) and non-nuclear fire information developed under the task “Industrial Fire Experience” (see Section 3.6).

The early results of this task are expected to support the development of the FRA portion of NFPA 805. The task is also expected to be useful as a pilot study for future investigations of model-based approaches for fire frequency estimation.

## 3.4 Fire Modeling Toolbox: Input Data and Assessment

### 3.4.1 Background

Prediction of the hazardous environment induced by a fire and of the response of critical equipment to this environment is an important part of FRA. As discussed in Ref. 12, some of the key uncertainties in these predictions are due to sparseness of and weaknesses in basic data needed to assess: a) the flammability and damageability characteristics of the equipment under fire conditions, and b) the validity of currently available physical models for predicting the fire-induced environment. Two approaches for addressing these problems are the improved processing of data currently available and the collection of additional relevant data.

Numerous experiments have been performed to collect various data relevant to the thermal behavior and effects of fires in nuclear power plants. However, there are three problems with these data. First, in some cases, the data from these experiments have not been processed to allow their use by analysts [26]. Second, the experiments were not usually performed with the needs of fire modeling, let alone FRA modeling, in mind. (This means that direct measurements of key model parameters may not have been performed.) Third, related to the second concern, weaknesses in the experimental processes (from an FRA modeling perspective) have not been characterized. (For example, the use of bare thermocouples above cable jackets can lead to optimistic biases when the reported temperatures at the time of cable damage are used in an FRA as cable damage temperatures.) The latter two concerns do not mean that the experimental results are useless; the Bayesian perspective of probabilistic risk assessment in general (and FRA in particular) encourages the use of all relevant forms of evidence (with appropriate biasing and weighting). The concerns do mean that data processing will require not only transcription of raw data into appropriate media and formats, but also characterization from an FRA perspective.

Some work has been performed on non-thermal effects of fire. This work has led to identification of potential failure modes of electronic equipment due to smoke effects (e.g.,

[27,28]). It has not yet led to characterizations of the fragilities of key equipment that can be directly used in FRAs.<sup>7</sup> Additional work is needed to develop these fragilities.

### 3.4.2 Task Scope

The emphasis of this task is on the collection and processing of data from previously performed experiments (or, in the case of smoke effects, from a limited set of new, small scale experiments). The issue of developing improved guidance for using existing fire models is addressed in Section 3.11; the issue of using advanced fire models is addressed in Section 3.14.

### 3.4.3 Task Objectives

- ! Collect and characterize available experimental data potentially relevant to the prediction of electrical cable flammability and thermal fragility.
- ! Collect and characterize available experimental data potentially relevant to the prediction of the thermal fragility of other potentially risk significant nuclear power plant components.
- ! Collect and characterize available experimental data potentially relevant to the assessment of model uncertainties in current fire environment models.
- ! Process and publish the Sandia base line fire model validation data (see Ref. 29) in a format suitable for its use by analysts to validate fire models used in FRAs.
- ! Generate experimental data needed to assess the smoke fragility of potentially risk significant nuclear power plant components.
- ! Collect and characterize available experimental data potentially relevant to the assessment of fire heat release rates.

### 3.4.4 Schedule and Lead

Start Date	July 1998
Completion Date	A draft final letter report (for all data other than the heat release rates) is due September 30, 1999.
Lead	S. Nowlen, SNL

### 3.4.5 Outputs and Interactions

The principle outputs of this task are a database containing: a) physical properties of key components (including cables) relevant to fragility and flammability, and b) a

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<sup>7</sup>The "fragility" of a component is the probability that the component will fail at a given level of environmental stressor.

characterization of the data to enable its confident use in various FRA applications; a publication of the fire environment data generated by the SNL base line validation tests and evaluations of fire modeling issues (e.g., appropriate values for the heat loss factor used in FIVE) based on these data; and the identification of conditions under which smoke damage to components may be risk significant. The physical properties data will be used in the task "IEEE-383 Rated Cable Fire Frequency Analysis: Feasibility Study" (see Section 3.3).

The results of this task have been used to support NRC/industry interactions concerning the resolution of generic requests for additional information generated during the IPEEE review process. The results are also expected to support the development of the FRA portion of NFPA 805.

### 3.5 Experience from Major Fires

#### 3.5.1 Background

A number of safety significant fires have occurred in U.S. and international nuclear power plants (e.g., see Refs. 30 and 31). While these events have been studied from a fire protection point of view, current FRAs tend to make limited use of the information obtained from these events. For example, counts of events are used to estimate fire frequencies, but the descriptions of many events have not been seriously studied to determine if changes in the FRA models or even basic FRA structure are warranted.

It is anticipated that a review of serious fire events from an FRA perspective will yield useful feedback on areas previously identified as being potentially important [12]. It may also identify previously unrecognized areas where improvements are needed.

#### 3.5.2 Task Scope

This task employs a case study approach to learning from experience. It is not intended to develop conclusions based on statistical analyses of data. Rather, conclusions will be drawn based on a detailed review of event descriptions (and other relevant information) and a consideration of the current FRA state of the art.

Serious international fires will be reviewed as part of this task. However, only conclusions which are relevant to U.S. nuclear power plants and FRAs will be developed.

#### 3.5.3 Task Objectives

- ! Identify key fire risk and FRA insights from serious U.S. and international nuclear power plant fires.
- ! Develop recommendations for FRA improvements and areas for further investigation.

#### 3.5.4 Schedule and Lead

Start Date	July 1998
Completion Date	The draft final letter report is due June 30, 1999.
Lead	M. Kazarians, Kazarians and Associates.

#### 3.5.5 Outputs and Interactions

The principle outputs of this task are insights concerning current FRA structure and methods. These insights will be used in the planning of future fire risk research activities, and should be useful in the development of the FRA portion of NFPA 805. This task will interact with the task "Risk Significance of Turbine Building Fires" (see Section 3.12).

### 3.6 Industrial Fire Experience

#### 3.6.1 Background

Reportable nuclear power plant fires are not frequent events; the average occurrence rate is on the order of 0.1 per plant-year [32]. The frequency of potentially risk significant fires is considerably lower. Thus, current FRA characterizations of the relative likelihood and progression of nuclear power plant fire scenarios are largely model- rather than experience-based. To reduce the uncertainties in these characterizations, it is useful to review the experience from non-nuclear industrial fires involving equipment and occupancies similar to those found in nuclear power plants. Such a review can provide useful qualitative information (e.g., how well do operators perform in degraded environments) as well as indications of the relative likelihood of different scenarios (e.g., low intensity vs. severe switchgear fires). As discussed in Ref. 33, it is not expected that the review will necessarily lead to quantitative data that can be directly used in estimates of fire scenario frequencies; the non-nuclear information sources appear to be in such a form that resource requirements for such an effort would be considerable.

#### 3.6.2 Task Scope

This task focuses on industrial fire scenarios and issues which are both relevant to and potentially risk significant for nuclear power plants. The following fire scenarios and fire protection elements are addressed: cable fires, low- to medium-voltage switchgear fires, low- to medium-voltage transformer fires, control room fires, and fire barriers.

#### 3.6.3 Task Objective

To collect and evaluate industrial data relevant to the analyses of specific nuclear power plant fire scenarios.

#### 3.6.4 Schedule and Lead

Start Date	April 1999
Completion Dates	The effort related to cable fires, and the effort related to switchgear and transformer fires, are both to be completed by September 30, 1999. The effort related to fire barriers is to be completed by March 31, 2000. The effort related to control room fires is to be completed by May 30, 2000. The draft final letter report documenting the results of each subtask is due August 30, 2000.
Lead	S.P. Nowlen, SNL

#### 3.6.5 Outputs and Interactions

The outputs of this task include insights regarding fire causes, duration, extent of damage caused, secondary fires, non-thermal impacts on other equipment, barrier performance, operator performance, and the relationship between fire frequency and magnitude. The task will also result in recommendations as to how the results of the data review should be used in nuclear power plant fire risk assessments. The results of this task feed into the following tasks:

- ! Tools for Fire Detection and Suppression Analysis (Section 3.2)
- ! IEEE-383 Rated Cable Fire Frequency Analysis: Feasibility Study (Section 3.3)
- ! Frequency and Characteristics of Switchgear and Transformer Fires (Section 3.7)
- ! Fire Barrier Reliability Model Development and Application (Section 3.8)

### 3.7 Frequency and Characteristics of Switchgear and Transformer Fires

#### 3.7.1 Background

Fires involving low- to medium-voltage (# 6.19kV) electrical switchgear (including motor control centers) are often important contributors to fire risk. However, there is considerable uncertainty as to how switchgear fires should be modeled (as a hazard to other components in the area). Many IPEEEs have selected a heat release rate of 69 kW (65 Btu/s) for their switchgear fires, based on the results of a number of Sandia National Laboratories (SNL) tests characterizing the heat release rate of electrical panel fires [34,35]]. This value comes from the lower end of the full range of SNL results. Other SNL tests led to heat release rates greater than 1.3 MW (1200 Btu/s). The 69 kW value represents the burning of a single bundle of IEEE-383 qualified cables; fires involving more fuel will naturally be greater in magnitude.

Indoor transformers can be found in switchgear rooms. In at least one case, an oil-filled transformer is located in a room containing cables for both safe shutdown trains. There is considerable uncertainty concerning the heat release rates of indoor transformer fires; Ref. 16 recommends a rate of < 69 kW (65 Btu/s) for dry-type, cast-resin transformers because the fire is assumed to be less severe than an electrical cabinet fire. For oil-filled transformers, Ref. 16 recommends a rate of 142 kW (135 Btu/s).

Besides data uncertainties, the concern with the current FRA treatments is that they treat switchgear and transformer fires essentially as pool fires. They do not account for the events leading up to the fire. In particular, if the fire is started by an electrical fault, the scenario can involve the overheating and ignition of cables far removed from the component. In the case of oil-filled transformer fires, an energetic fault can lead to a spray of burning oil rather than a pool. Furthermore, the blast and missiles from an energetic fault can cause direct mechanical damage to nearby components.

### 3.7.2 Task Scope

This task addresses the frequency and magnitude of low- to medium-voltage switchgear (480V to 6900V) and indoor transformers feeding these switchgear. It addresses both fire and blast effects.

### 3.7.3 Task Objectives

- ! Develop frequency-magnitude relationships for switchgear and transformer fires.
- ! Develop a simple method for addressing the non-thermal effects of switchgear and transformer energetic faults.

### 3.7.4 Schedule and Lead

Start Date	July 1999
Completion Date	The draft final letter report is due March 31, 2000.
Lead	S.P. Nowlen, SNL

### 3.7.5 Outputs and Interactions

The principle outputs of this task follow from the task objectives: frequency-magnitude relationships for low- to medium-voltage switchgear and transformer fires, and a simple method for addressing the non-thermal effects of switchgear and transformer energetic faults.

This task will use non-nuclear switchgear and transformer fire information developed under the task “Industrial Fire Experience” (see Section 3.6).

The early results of this task will support the development of the FRA portion of NFPA 805 and the development of the insights report to be developed by the IPEEE program (see Section 4).

## 3.8 Fire Barrier Reliability Model Development and Application

### 3.8.1 Background

The treatment of local fire barriers varies in current FRAs. Approaches include: a) fully crediting the barriers if they provide separation as required by Appendix R and if the barriers are included in a fire barrier surveillance program (FIVE, pp. 2-1, 5-1, 6-2 [23]); b) using simple

heat transfer models (not a common approach); c) crediting barriers for delaying fire-induced damage and ignition based on experimental results for a limited number of barrier systems (Ref. 16, p. J-2). The problem with the first approach is that it doesn't allow for the finite probability of failure of the barrier. The problem with the second and third approaches is that they do not account for key factors (e.g., mechanical construction details, material behavior under fire conditions) which affect performance of many current barrier systems. The third approach also has the problem of using experimental results in situations not directly covered by the experiments (e.g., different fire severities, geometries).

Intercompartment fire barriers are typically fully credited when the barriers separate fire areas. Some studies employ reliability estimates for specific barrier elements (penetration seals, dampers, doors); these estimates were derived as part of the Risk Methods Integration Evaluation Program (RMIEP) program and are quoted in Refs. 15 and 22. Many studies fully credit barriers between fire zones under certain conditions (e.g., see FIVE, p. 5-8 [23]). The problem with the first approach is that it doesn't allow for the finite probability of failure of the barrier. A key problem with the second approach is that the formal technical basis for the reliability estimates is unavailable. It is not clear if the estimates were correctly derived. (Note that it is the authors' recollection that the Ref. 15/22 fire barrier failure probabilities were originally derived as barrier failure rates; they are being misapplied in FRAs.) The problem with the third approach is that there is no apparent, documented technical basis for the specific conditions provided (e.g., a 1-hour barrier provides adequate separation when the compartment fire loading is  $<80,000$  Btu/ft<sup>2</sup>).

The resolution of these problems is related to the assessment of penetration seals currently being performed by the NRC staff (see Section 3.13).

### 3.8.2 Task Scope

This task addresses both local and intercompartment fire barriers. Regarding local barriers, the focus is on barriers protecting electrical cables. These include wrappings, coatings, cable tray covers, constructed enclosures, and conduits. Regarding intercompartment barriers, active elements (e.g., dampers and fire doors) and passive elements will be addressed.

### 3.8.3 Task Objectives

- ! Develop a screening model for predicting the performance of local fire barriers under exposure fire conditions. The model will address probabilistic issues (e.g., barrier construction and installation) as well as phenomenological issues (e.g., exposure fire severity).
- ! Estimate the probability of failure (on demand) of fire dampers, fire doors, and penetration seals for challenging fire scenarios.

#### 3.8.4 Schedule and Lead

Start Date	October 1999
Completion Date	The draft final letter report is due September 30, 2000.
Lead	S.P. Nowlen, SNL

#### 3.8.5 Outputs and Interactions

The principle outputs of this task follow from the task objectives: a screening model for predicting the performance of local fire barriers under exposure fire conditions; and estimates of the reliability of fire dampers, fire doors, and penetration seals for challenging fire scenarios.

This task will use non-nuclear information on fire barrier performance generated by the task "Industrial Fire Experience" (see Section 3.6). It will also interact with the task "Penetration Seals" (see Section 3.13), and is expected to interact with the task "Tools for Fire Detection and Suppression Analysis" (see Section 3.2).

The results of this task will be useful to potential future NRC/industry activities concerning the application of FRA in the resolution of fire protection issues (including, for example, the evaluation of barrier degradations).

### 3.9 Integrated Model and Parameter Uncertainty

#### 3.9.1 Background

When model predictions are used to support decision making, it is sometimes useful to explicitly quantify the uncertainties in these predictions.<sup>8</sup> Methods for estimating "output parameter uncertainty," i.e., uncertainty in the model output due to uncertainties in the values of model input parameters, are well known and routinely applied in many situations. On the other hand, there currently is no consensus concerning formal methods for estimating "output model uncertainty," i.e., the additional output uncertainty due to approximations inherent in a given model.<sup>9</sup> Methods of varying formality have been used in practical analyses. For example, Ref. 36 uses experimental data and model predictions in non-statistical analyses of biases and uncertainties in submodel outputs. However, this represents only one approach for dealing with output model uncertainty. Ref. 37 presents many viewpoints on how model

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<sup>8</sup>It is assumed that the uncertainties in model predictions are quantified by a (joint) probability distribution function for the model output variable(s). For example, the joint density function for an output vector  $\mathbf{Z}$  is  $f_{\mathbf{Z}}(\mathbf{z})d\mathbf{z} / P\{\mathbf{z} \in \mathbf{Z} < \mathbf{z}+d\mathbf{z}\}$ .

<sup>9</sup>In the literature, "output parameter uncertainty" and "output model uncertainty" are usually referred to as "parameter uncertainty" and "model uncertainty." To avoid confusion, we will use the latter terms to refer to the uncertainties in the parameter values and model structure, respectively, and not the resulting uncertainties in the model predictions.



uncertainty and, to a lesser extent, output model uncertainty, should be defined and addressed in general situations.

In the case of fire model prediction, simulation codes are available to predict the dynamic behavior of variables that are, in principle, measureable. Furthermore, limited amounts of experimental data potentially useful for estimating output model uncertainty are also available. (A typical data set might look like the trace shown in Figure 2.) However, estimation is not straightforward for a number of reasons.

- ! The experiments do not cover all possible situations to which the model will be applied. This can affect the applicability of any experimentally-derived output model uncertainty distribution.
- ! The values of the model parameters needed to simulate the experiments may not be well known. (Note that the experiments are not necessarily performed for the sake of model validation.) It may therefore be unclear as to how much of the difference between model predictions and experimental data is due to the parameter uncertainty and how much is due to the model uncertainty.
- ! As discussed in Ref. 37, there currently is a controversy as to how model uncertainty (and therefore output model uncertainty) should be precisely defined and therefore quantified. According to one school of thought, the probability that a given model is “valid” or “acceptable” needs to be estimated. According to another school of thought, estimation of the conditional probability that an output variable takes on a value in a given range, given the prediction of a model, is key.

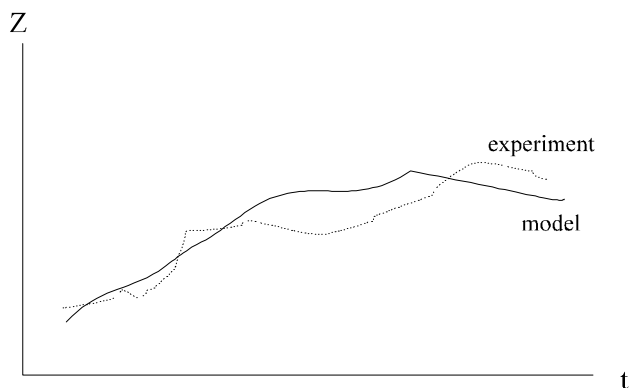


Figure 2. Form of data available for quantifying output model uncertainty

A relatively simple approach for quantifying uncertainty in model predictions in the presence of model uncertainty and parameter uncertainty is proposed in Ref. 38. However,

this approach has not been fully tested. Furthermore, the relationship between the approach and the fundamental frameworks discussed in Ref. 37 has not been investigated.

Work on this task is being performed as part of a cooperative research agreement with the University of Maryland (see Section 4.6).

### 3.9.2 Task Scope

The first year of this task addresses the development of a framework which can be used in a broad variety of situations (e.g., thermal hydraulic analysis of reactor transients) as well as fire modeling. The application of this framework to develop estimates of output model uncertainty will be addressed in the second year of effort.

### 3.9.3 Task Objectives

- ! Evaluate the ability of various methodologies to assess model uncertainty to the same level as parameter uncertainties, and formulate a framework under which their combined uncertainties can be assessed.
- ! Demonstrate how the formulated framework can be applied to address real issues involving combined parameter and model uncertainties.

### 3.9.4 Schedule and Lead

Start Date	August 24, 1998
Completion Date	Framework completion: August 23, 1999 Framework demonstration: August 23, 2000
Lead	A. Mosleh, University of Maryland

### 3.9.5 Outputs and Interactions

The principal outputs of this task are: a) a framework for evaluating model and parameter uncertainties, and b) a demonstration of that framework for a realistic fire scenario.

This task is expected to interact with the task "Fire Model Limitations and Application Guidance" (see Section 3.11). Its results will be useful to potential future NRC/industry activities concerning the application of FRA in the resolution of fire protection issues.

## 3.10 Frequency of Challenging Fires

### 3.10.1 Background

One of the key issues in fire frequency analysis for FRA is the reduction of fire frequencies performed in most detailed FRAs to accommodate the fact that not all fires are risk significant, i.e., that a fire must have the proper location and severity characteristics to be a potentially important cause of critical equipment damage. In a number of FRAs, "location fractions" are employed to reduce plant area-based fire frequencies to account for geometrical

factors; other FRAs use plant component-based fire frequencies for this same purpose. Regarding fire severity, “severity fractions” are widely used to address the fraction of fires (in a given compartment or involving a given component) that have the potential to cause significant damage in a relatively short amount of time.

Current reduction factors used to address location and severity considerations can reduce the compartment fire frequencies (the  $\lambda_i$ ) by one or more orders of magnitude. However, the basis for these reduction factors is not strong. Early studies (e.g., Ref. 39) relied heavily on analyst judgment. Attempts to reduce the influence of judgment have led to: a) the component-based approach to fire frequency, employed in the FIVE methodology [23], and b) event-based estimation of severity fractions (e.g., [16,40]). However, these approaches are not without problems. In particular, the concerns with the event-based treatment of the severity issue include: ambiguity in the data (qualitative event narratives are used to determine if a given fire was severe); possible double-counting of the impact of suppression in the data (effective suppression may be the reason why a particular fire was not reported as being severe, but fire suppression is modeled separately in the FRA); neglect of possibly significant differences between conditions (e.g., fuel bed geometry) of the event and those of the situation being analyzed in the FRA which can affect the severity of the fire; and scarcity of data for the large, transient-fueled fires that have been predicted to dominate fire risk in a number of studies.

The preceding issues deal with the problem of quantifying the likelihood of fire occurrence. A related issue concerns the establishment of conditions for the next stage of the FRA, the estimation of the likelihood of equipment damage. Current methods for performing this next stage generally rely upon fire environment simulation models, and these models require the specification of the initial conditions for a given simulation. The problem is that current fire frequency analyses provide, at most, the frequency of “small” and “large” fires in a specified compartment or involving a specified component. They do not provide the physical characteristics associated with these “small” and “large” fires needed by the simulation models. This ambiguous interface between the fire frequency and equipment damage analyses allows significant analyst discretion. For example, the Indian Point study [39] assumes that “large” fires have a severity equivalent to a 2-foot diameter oil fire, while the Surry NUREG-1150 study [41] assumes that this is the equivalent severity of “small” fires. In a recent IPEEE, all main feed pump fires are analyzed as if they involve the release of a pump’s entire lube oil inventory into a diked sump area and subsequent ignition of the oil; there is no distinction between large and small fires.

Fire frequencies have, to date, been treated as empirical parameters which can be directly estimated from data. The issues discussed above show that this treatment needs to be re-examined. A more mechanistic, systems modeling approach which, for different locations within a plant, specifically addresses the possible scenarios leading to fire ignition and the different outcomes of these scenarios, and does so within the constraint of available data, may be appropriate.

It is expected that the improved methodology developed as a result of this task will result in the definition of fire scenarios applicable to a given location in a plant, the frequency of such scenarios, and the characteristics of such scenarios. The characteristics are expected to be specified in terms that will support subsequent fire modeling, i.e., they will provide (at least in part) the initial conditions for models predicting the behavior of the fire following

initiation. The method is expected to employ U.S. nuclear power plant historical fire event data and/or other forms of technical information from other sources (e.g., non-nuclear industrial facilities), as appropriate. The methodology is also expected to address the explicit quantification of uncertainties in results.

### 3.10.2 Task Scope

This task covers both an initial project phase (one or more feasibility studies) for the development of the improved methodology, as well as a second project phase (which covers actual methodology development and demonstration).

### 3.10.3 Task Objectives

- ! Determine the feasibility of developing a practical, improved methodology for defining, characterizing, and quantifying the frequency of challenging nuclear power plant fire scenarios.
- ! Develop and demonstrate the methodology.

### 3.10.4 Schedule and Lead

Start Date	Phase 1: work is expected to start July 1, 1999
Completion Date	Phase 1: work should be completed 3 months after contract issuance Phase 2: work should be completed and documented by September 30, 2000
Lead	to be determined

### 3.10.5 Outputs and Interactions

The principle output of this task is a methodology for defining, characterizing, and quantifying the frequency of challenging nuclear power plant fire scenarios.

The results of this task will be useful to potential future NRC/industry activities concerning the application of FRA in the resolution of fire protection issues.

## 3.11 Fire Model Limitations and Application Guidance

### 3.11.1 Background

In FRA, characterization of the fire-induced hazardous environment requires the estimation of the time-dependent temperature and heat fluxes in the neighborhood of the safety equipment of interest (i.e., the “targets”). This requires the treatment of a variety of phenomena as the fire grows in size and severity, including the spread of fire over the initiating component (or fuel bed), the characteristics of the fire plume and ceiling jet, the spread of the fire to non-contiguous components, the development of a hot gas layer, and the propagation of the hot gas layer or fire to neighboring compartments. It also requires an appropriate treatment of uncertainties in the structure and parameters of the models used to perform

the analysis.

To date, U.S. nuclear power plant FRAs have used quite simple zone model-based tools, e.g., the correlations provided as part of the FIVE methodology [23] and the COMPBRN computer code [42,43], to predict the thermal environment due to a variety of fire sources, including cable tray, electrical cabinet, and oil pool fires. However, it is not always recognized in FRAs that these tools have been developed to address specific classes of fire problems and are not applicable to all situations. For example, the inherent modeling assumptions in both FIVE and COMPBRN do not address many practical complexities (e.g., obstructions in the fire plume, complex compartment geometry, complexities in forced ventilation flow, physical movement of fuel, room flashover) which can be important in some analyses. Further, the correlations employed implicitly or explicitly by these models are not appropriate for all situations. Some scenarios of potential concern include very small fires (e.g., single wire electrical insulation fires), very large fires (e.g., very large oil spill fires), or elevated fires. Unfortunately, the limitations of these simple models have not been succinctly characterized to inform FRA analysts, many of whom may not have strong background in fire science, when they should be wary of the model predictions. Improved guidance is needed to assist users in making appropriate use of these models and in interpreting their results.

### 3.11.2 Task Scope

This task addresses the models currently used in FRAs and publicly available models of comparable complexity which might be used in FRAs (e.g., CFAST [44]).

### 3.11.3 Task Objectives

- ! To identify the areas of uncertainty and limitations associated with fire models which are either: a) currently used in FRAs, or b) might be used in future FRAs.
- ! To develop improved guidance for using these fire models in FRAs.

### 3.11.4 Schedule and Lead

Start Date	October 1999
Completion Date	Work should be completed and documented by September 30, 2000
Lead	to be determined

### 3.11.5 Outputs and Interactions

This task will result in improved guidance for the use of fire models in FRA. This task will take input from the task "Risk Significance of Turbine Building Fires" (see Section 3.12) and will interact with the task "Integrated Model and Parameter Uncertainty" (see Section 3.9). It will also take input from the fire modeling portion of NFPA 805.

The results of this task will be useful to potential future NRC/industry activities concerning the application of FRA in the resolution of fire protection issues.

### 3.12 Risk Significance of Turbine Building Fires

#### 3.12.1 Background

Historical turbine building fires (e.g., the Narora fire [31]) and a number of IPEEEs (e.g., [45]) show that severe turbine building fires can be important contributors to risk. Potential concerns with the adequacy of fire risk assessment (FRA) tools for these fires are discussed in Ref. 10; they include the lack of knowledge concerning the frequency-magnitude relationship for turbine building fires and the adequacy of current FRA tools for predicting the environment induced by a severe turbine building fire.<sup>10</sup> Partly because of these concerns, the overall risk contribution from turbine building fires at any given plant is uncertain.

#### 3.12.2 Task Scope

This task will primarily rely upon reviews of existing reports. The need for additional information gathering activities (e.g., walkdowns) and analyses will be determined from these reviews.

#### 3.12.3 Task Objectives

- ! Improve the technical basis for fire risk assessments of turbine building fires.
- ! Assess the risk significance of turbine building fires.
- ! Develop recommendations for FRA improvements and areas for further investigation.

#### 3.12.4 Schedule and Lead

Start Date	August 14, 1998
Completion Date	Work should be completed and documented by June 30, 1999
Lead	M. Dey, NRC

#### 3.12.5 Outputs and Interactions

The principle outputs of this task are an assessment of the risk significance of turbine building fires, and recommendations concerning the need and direction for FRA improvements in this area.

This task interacts with the task “Experience from Major Fires” (see Section 3.5). It will provide input (in terms of key fire scenarios) to the task “Fire Model Limitations and Application Guidance” (see Section 3.11).

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<sup>10</sup>While the physical properties of oil are reasonably well understood, the ability of current FRA models to accurately predict the behavior of very large oil fires under realistic plant conditions is of concern, due to such complications as flame obstructions and oxygen starvation (both local and global).

The results of this work will support the development of the FRA portion of NFPA 805 and the development of the insights report to be developed by the IPEEE program.

### 3.13. Penetration Seals

#### 3.13.1 Background

Between 1994 and 1998, the NRC staff performed a number of technical assessments of fire penetration seals to address reports of potential problems, to determine if there were any problems of safety significance, and to determine if NRC requirements, review guidance, and inspection procedures were adequate [46]. During the resolution process of this issue, questions were raised by the NRC's Advisory Committee on Reactor Safeguards regarding the risk significance of the issues and problems, and whether risk-informed approaches to issue resolution were available [47].

#### 3.13.2 Task Scope

This task represents a feasibility study focused on current FRA methods, tools, and data. If improvements are required, these will be addressed in a later task.

#### 3.13.3 Task Objectives

- ! Determine the extent to which current fire risk assessment methods and data can be confidently used to support prioritization of penetration seals for inspection.
- ! Identify issues (if any) requiring research to improve risk-informed prioritization and/or confidence in such a prioritization.

#### 3.13.4 Schedule and Lead

Start Date	August 14, 1998
Completion Date	Work should be completed and documented by June 30, 1999
Lead	M. Dey, NRC

#### 3.13.5 Inputs and Outputs

The principle outputs of this task are an assessment of the ability of current FRA methods, tools, and data to support the prioritization of penetration seals for inspection; and recommendations concerning the need and direction for future research.

This task will interact with the task "Fire Barrier Reliability Model Development and Application" (see Section 3.8).

The results of this work will support the development of the FRA portion of NFPA 805 and the development of the insights report to be developed by the IPEEE program.

### 3.14 Risk Significance of Multiple Unit Interactions

#### 3.14.1 Problem Statement

The results of a number of IPEEE reviews show that the risk implications of fire-related interactions among multiple units are potentially significant and need to be better understood. Of primary interest are scenarios where a single fire can induce simultaneous transients in multiple units. Although the frequencies of such scenarios are expected to be low, their potential consequences are significantly greater than those of scenarios affecting only one unit.

It is not clear if these scenarios have been adequately addressed in the IPEEEs. (For example, those IPEEEs which have used scenario screening frequencies of  $10^{-6}/\text{yr}$  may have screened out these scenarios without considering their potential effect.)

#### 3.14.2 Task Scope

This task will primarily rely upon reviews of existing reports and limited exercises of FRA models. The need for additional information gathering activities (e.g., walkdowns) and analyses will be determined from these reviews.

#### 3.14.3 Task Objectives

- ! Identify plants where a single, severe fire may simultaneously affect multiple units and assess the risk implications of such fires.
- ! Develop recommendations for additional research.

#### 3.14.4 Schedule and Lead

Start Date	May 1, 1999
Completion Date	Work should be completed and documented by September 30, 1999
Lead	H. Woods, NRC

#### 3.14.5 Outputs and Interactions

The principle outputs of this task are an assessment (based on available reports) of the risk contribution from fire scenarios involving multiple unit interactions; and recommendations concerning the need and direction for future research.

The results of this work will support the development of the FRA portion of NFPA 805 and the development of the insights report to be developed by the IPEEE program.



### 3.15 Use of Advanced Fire Models in Fire Risk Assessment

#### 3.15.1 Background

As discussed in Section 3.11, the modeling assumptions inherent in the fire models currently used in FRAs do not address many practical issues which can be important in some analyses. A number of these issues, e.g., obstructions in the fire plume, complex compartment geometry, complexities in forced ventilation flow, are addressed by state of the art "field models" (e.g., the National Institute of Standards and Technology's Large Eddy Simulation code [48]) which explicitly address the computational fluid dynamics aspects of fire. Although these models are currently too resource intensive (including analyst time as well as computation time) for routine use in FRAs, it appears that they should be useful tools for evaluating, and even modifying, the simpler FRA models.

The NRC is in the process of establishing a memorandum of understanding with the National Institute of Standards and Technology (NIST) to support this task. It is anticipated that NIST staff will, in exchange for the SNL base line validation data provided by the NRC (see Section 3.4), support technology transfer to the NRC by assisting in the analysis of a number of the base line experiments.

#### 3.15.2 Task Scope

This task investigates the feasibility and role of state of the art field models in FRA. It also involves the performance of sample calculations for fire scenarios of interest to FRA. The integration of field models into FRA will be addressed in future tasks.

#### 3.15.3 Task Objectives

- ! Identify specific FRA areas where field models could be used to improve confidence in FRA results.
- ! Use a selected field model to model fire experiments of interest to FRA (including the SNL base line validation tests [29]).
- ! Develop recommendations concerning the appropriate role of current field models in FRA and what work needs to be done to allow such a use.

#### 3.15.4 Schedule and Lead

Start Date	October 1, 1999
Completion Date	Work should be completed and documented by September 30, 2000
Lead	to be determined, for both NRC and NIST

### 3.15.5 Outputs and Interactions

The principle outputs of this task are: insights concerning the effective use of current field models in FRAs, and recommendations for enabling such use. The task will also result in the transfer of state of the art fire modeling technology to the NRC.

Input to the task will be provided by the fire modeling portion of NFPA 805. The results of this task will be useful to potential future NRC/industry activities concerning the application of FRA in the resolution of fire protection issues.

Table 1. Fire Risk Research Program Technical Tasks, FY 1998-2000

Lead Org.	Task Title
SNL	Tools for circuit failure mode and likelihood analysis
SNL	Tools for fire detection and suppression analysis
SNL	IEEE-383 rated cable fire frequency analysis: feasibility study
SNL	Fire modeling toolbox: input data and assessment
SNL	Experience from major fires
SNL	Industrial fire experience
SNL	Frequency and characteristics of switchgear and transformer fires
SNL	Fire barrier reliability model development and application
UMd	Integrated model and parameter uncertainty
TBD	Frequency of challenging fires
TBD	Fire model limitations and application guidance
NRC	Risk significance of turbine building fires
NRC	Penetration seals
NRC	Risk significance of multiple unit interactions
NRC	Use of advanced fire models in fire risk assessment

SNL = Sandia National Laboratories

TBD = to be determined

UMd = University of Maryland

USNRC = U.S. Nuclear Regulatory Commission

Task Providing Input	Task Requiring Input													
	Tools for circuit failure mode and likelihood analysis	Tools for fire detection and suppression analysis	IEEE-383 rated cable fire frequency analysis: feasibility study	Fire modeling toolbox: input data and assessment	Experience from major fires	Industrial fire experience	Frequency and characteristics of switchgear and transformer fires	Fire barrier reliability model development and application	Integrated model and parameter uncertainty	Frequency of challenging fires	Fire model limitations and application guidance	Risk significance of turbine building fires	Penetration seals	Risk significance of multiple unit interactions
Tools for circuit failure mode and likelihood analysis														
Tools for fire detection and suppression analysis														
IEEE-383 rated cable fire frequency analysis: feasibility study														
Fire modeling toolbox: input data and assessment														
Experience from major fires														
Industrial fire experience														
Frequency and characteristics of switchgear and transformer fires														
Fire barrier reliability model development and application														
Integrated model and parameter uncertainty														
Frequency of challenging fires														
Fire model limitations and application guidance														
Risk significance of turbine building fires														
Penetration seals														
Risk significance of multiple unit interactions														
Use of advanced fire models in fire risk assessment														

Figure 3. Fire Risk Research Program Task Interactions

## 4. INTERACTIONS WITH RELEVANT FIRE PROTECTION ACTIVITIES

### 4.1 IPEEE Review

As stated in Refs. 49 and 50, the primary goal of the IPEEE program is for licensees to identify plant-specific “external event” (including internal fires) vulnerabilities to severe accidents that could be fixed with low-cost improvements. The Office of Nuclear Regulatory Research (RES) is responsible for the review of licensee submittals. The review process includes the performance of initial reviews, the development of requests for additional information (RAIs), if needed, and the review of the licensees’ RAI responses. The resolution of a generic set of RAIs arising from licensees’ implementation of the FRA guidance provided in Ref. 16 is scheduled for early in the third quarter of FY 1999. Completion of a final draft report on the insights gained from the IPEEE process is scheduled for early in the fourth quarter of FY 2000.

The RES IPEEE program has provided input to the identification and prioritization of potential research topics relevant to the fire risk research program [12]. Specific topics identified during the IPEEE submittal reviews and included in the research program include the feasibility study for IEEE-383 rated cables (Section 3.3), the investigation of turbine building fires (Section 3.12), and the investigation of multi-unit fires (Section 3.14).

For its part, the fire risk research program has provided information supporting the resolution of the generic RAIs mentioned above. In particular, it has provided an assessment of Ref. 16’s recommendation concerning the proper “heat loss factor” to use in determining hot gas layer temperatures [51]. This assessment was performed using data from the SNL base line validation tests that were processed as part of the task “Fire modeling toolbox: input data and assessment” (see Section 3.4). A number of research program task results (e.g., circuit failure mode probabilities, cable flammability parameters), are also expected to support the development of the IPEEE insights report.

### 4.2 NFPA 805 Standard Development

As described in Ref. 6 and discussed in Section 1, the National Fire Protection Association is currently developing a risk-informed, performance-based, consensus fire protection standard for existing nuclear power plants. This standard (NFPA 805) will include a description of FRA methods, tools, and data that are acceptable for use in implementing the standard. (The appendix containing that description is currently under development.) The NRC staff is developing a rulemaking process for using NFPA 805 as part of a risk-informed, performance-based alternative to NRC’s current fire protection regulations.

According to the current schedule, all comments on NFPA 805 must be resolved by September 24, 1999. Any relevant results from the fire risk research program generated prior to that time will be fed into the standard development process, as appropriate, through NRC representatives on the standards committee.

### 4.3 Other RES Activities in Risk-Informed, Performance-Based Fire Protection

RES staff are in the process of finalizing a report on possible areas where risk information might be used to improve its fire protection regulatory requirements and processes

[52]. The report identifies a number of candidate applications (e.g., the evaluation of safe separation distance) and performs preliminary analyses of these applications using currently available methods and tools. It is expected that the fire risk research program will provide an improved technical basis for addressing these applications. Note that: a) Ref. 8 provides Nuclear Energy Institute (NEI) feedback concerning its prioritization of potential applications, and b) NEI indicated at March 25, 1999 public meeting that it will not be able to support work on FRA applications (aside from the development of NFPA 805 and an assessment of fire-induced circuit failures) until the summer of 1999, at the earliest [53].

#### 4.4 Other RES Research Activities

As discussed in Section 2.3, RES has a research program aimed at developing an improved human reliability analysis methodology (ATHEANA [17]). According to current plans, the ATHEANA methodology will be applied to FRA late in the third quarter of FY 1999. This application is currently expected to accomplish the following objectives.

- ! Characterize current FRA treatments of operator performance given complex fire response procedures.
- ! Develop insights regarding the risk associated with the impact of fires and fire-induced failures on operator situation assessment, decision making, and associated actions.
- ! Develop insights regarding the application of the ATHEANA methodology to fire scenarios.
- ! Develop recommendations for FRA improvements and areas for further investigation.

RES is also conducting an investigation of the effects of smoke on digital instrumentation and control (I&C) components [27,54]. This work has identified a number of potentially important failure mechanisms for these components. The fire risk research program will use the results of this work when developing recommendations concerning the need for and scope of future work on the risk contribution of fire scenarios involving smoke damage. (See Section 3.4, "Fire Modeling Toolbox: Input Data and Assessment.")

#### 4.5 Cooperation with Industry

On October 20, 1998, the NRC and the Electric Power Research Institute signed an addendum to their existing Memorandum of Understanding (MOU) on cooperative nuclear safety research. The MOU addendum addresses cooperative fire risk research and development (R&D); its objectives are: to ensure the timely exchange of information (e.g., objectives, milestones) on planned and ongoing activities; to ensure the sharing of data needed by the NRC and EPRI R&D programs; and to ensure the timely sharing of R&D results and tools.

Both programmatic and technical information exchanges are included in the program. Specific technical information exchanges include: NRC's provision of the SNL base line validation data to EPRI, and EPRI's provision of access to a fire events database being developed by Nuclear Electric Insurance Limited. Note that this database, when complete, is expected to address fire event counting concerns raised in Ref. 12. The industry's efforts

therefore allow the fire risk research program to avoid the expenditure of significant resources to address these concerns.

#### 4.6 Cooperation with Other U.S. Programs

The RES program includes a cooperative research activity with the University of Maryland in the area of uncertainty analysis. (See Section 3.9, "Integrated Model and Parameter Uncertainty.") This activity is being pursued under a broader cooperative agreement: Probabilistic Assessment and Applications (NRC Job Control Number K6007). As indicated in Section 3.9.4, the NRC has committed \$160K and the University of Maryland has committed \$70K. These commitments support faculty and graduate research assistants; they cover work on uncertainty analysis for reactor systems thermal hydraulic code applications, as well as uncertainty analysis for FRA.

The possibility of a cooperative activity with the National Institute of Standards and Technology (NIST) is also being pursued. (See Section 3.15, "Use of Advanced Fire Models in Fire Risk Assessment.") It is anticipated that the cooperation will involve the exchange of NRC-developed fire data for NIST staff assistance in developing NRC capabilities to use the NIST-developed Large Eddy Simulation code, a state-of-the-art field model.

#### 4.7 International Cooperation

RES has a number of formal interactions with international research programs relevant to nuclear power plant fire safety. Formal interactions include RES' participation on the Organization for Economic and Cooperation and Development (OECD)/Committee on the Safety of Nuclear Installations (CSNI)/Principal Working Group 5, which is developing an FRA state of the art report and RES' participation in the International Cooperative PRA Research Program (COOPRA). Through these activities, the fire risk research program has collected information on a number of subjects (e.g., the objectives, characteristics, and results of recent fire tests performed in France; fire event data from Canada) relevant to the program's objectives and activities.

#### 4.8 Regulatory Activities

The NRC Office of Nuclear Reactor Regulation (NRR) has a number of fire protection activities which could interact with the fire risk research program. Beyond the previously discussed IPEEE program (an NRR staff member is participating on the Senior Review Board) and the development of NFPA 805 and the associated rulemaking process, these activities include [55]:

- ! the development of a methodology to assess the risk significance of fire protection related inspections, and
- ! the resolution of the fire-induced circuit failures issue.

Regarding the first activity, RES staff involved with the fire risk research program have been participated in reviews of the methodology, and will likely be involved in future reviews and discussions of application issues. The initial development phase of the activity is expected to be completed by the middle of the third quarter of FY 1999.

Regarding the second activity, NRR has deferred issuing generic communications awaiting industry efforts to resolve the issue. The current NEI schedule [8] indicates the drafting of a risk-informed method for addressing fire-induced circuit failures by the second quarter of FY 1999, NRC and industry agreement on scope by the third quarter, and the issuance of a final analysis guideline by the first quarter of FY 2000. The results of the fire risk research program task "Tools for Circuit Failure Mode and Likelihood Analysis" (see Section 3.1), which are scheduled to be available by the end of September, 1999, are expected to support NRC/industry discussions.

It should be noted that ongoing NRR activities concerning the resolution of fire barrier issues could, in principle, be supported by a number of fire risk research program tasks, including "Fire Barrier Reliability Model Development and Application" (see Section 3.8). However, the current NRR schedule (a number of actions are scheduled for the March-April 1999 timeframe) and the RES staff and resource limitations prevent such support.

## 5. PROGRAM SUMMARY

Figure 4 shows the overall schedule for the fire risk research program tasks.

Task Description	98/3	98/4	99/1	99/2	99/3	99/4	00/1	00/2	00/3	00/4
Tools for circuit failure mode and likelihood analysis										
Tools for fire detection and suppression analysis										
IEEE-383 rated cable fire frequency analysis: feasibility study										
Fire modeling toolbox: input data and assessment										
Experience from major fires										
Industrial fire experience										
Frequency and characteristics of switchgear and transformer fires										
Fire barrier reliability model development and application										
Integrated model and parameter uncertainty										
Frequency of challenging fires										
Fire model limitations and application guidance										
Risk significance of turbine building fires										
Penetration seals										
Risk significance of multiple unit interactions										
Use of advanced fire models in fire risk assessment										

Figure 4. Overall Task Schedule



## 6. POTENTIAL FUTURE ACTIVITIES

SECY-98-230 [11] states that the currently approved fire risk research program runs from FY 1998 through FY 2000, and indicates that the NRC staff will seek Commission approval before initiating any further fire protection-related research activities. It should be recognized that, by the end of FY 2000, the research program will yield a set of FRA improvements and insights that will be useful in addressing specific fire protection issues. However, the program as currently defined does not provide a summary statement of the overall impact of the FRA improvements, nor does it provide a summary set of guidance for performing improved FRA. Furthermore, it does not complete the integration of advanced fire models (or their results) into FRA. These are important application gaps that will need to be addressed in order to support the increased use of risk-informed, performance-based methods in fire protection.

It is therefore expected that the staff will develop recommendations to pursue the following follow-on (post FY 2000) tasks.

- ! Fire risk requantification. This task will apply the results of the fire risk research program in a requantification of the fire risk for a selected plant. The objectives of the requantification will be to determine the risk impact associated with the FRA improvements and to develop insights concerning the application of the improved FRA methods and tools.
- ! FRA guidance development. This task will use the results of the fire risk research program to develop an improved guidance document for performing FRA. This document will support the standardization of FRA at a level of description more detailed than that currently envisioned for the NFPA 805 standard.
- ! Integration of advanced fire models into FRA. This task will use the results of the task "Use of Advanced Fire Models in Fire Risk Assessment" (see Section 3.15) to incorporate advanced fire models (or their results) into FRA.

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## APPENDIX A - Disposition of Potential Fire Protection Issues

Attachment 2 to SECY-97-127 lists and defines 12 potential fire protection issues raised in NRC's Fire Protection Task Action Plan (FPTAP). Attachment 2 to SECY-98-247 provides the NRC Staff's recommendations concerning the disposition of these potential issues. The following table shows this dispositioning and, in the case of issues assigned to the fire risk research program, identifies the task addressing the issue.

Issue	Disposition
Other Modes of Operation	Included in scope of NFPA 805.
Fire Impact on Reactor Safety	Addressed by IPEEE program.
Hot Shorts	Addressed by NRC circuit analysis resolution plan
Smoke Impact on Reactor Safety	Addressed by IPEEE program. Also being addressed by the following fire risk research tasks, the ATHEANA fire risk application, and the RES program on the effect of smoke on digital I&C components. - Tools for fire detection and suppression analysis - Fire modeling toolbox: input data and assessment
Testing/Compensatory Measures	Included in the scope of NFPA 805
Main Control Room/Cable Spreading Room Fire Interaction Analysis Methods	Addressed by IPEEE program. Also being addressed by the ATHEANA fire risk application.
Fire Detection Methods	Addressed by the following fire risk research tasks. - Tools for fire detection and suppression analysis - Use of advanced models in fire risk assessment
Analysis of Explosive Electrical Faults	Addressed by the following fire risk research tasks. - Industrial fire experience - Frequency and characteristics of switchgear and transformer fires
Reliability of Fire Barriers	Addressed by the IPEEE program. Also being addressed by the following fire risk research tasks. - Industrial fire experience - Fire barrier reliability model development and application
Broken/Leaking Flammable Gas Lines	Addressed by the IPEEE program.
Equipment Protection from Fire Suppression System Actuation	Addressed by the IPEEE program.
Seismic Fire Interactions	Addressed by the IPEEE program

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## APPENDIX B - Disposition of Potential Fire Risk Research Issues

Ref. B1 identifies 42 potential fire risk assessment (FRA) research issues, i.e., areas where work may be needed to achieve the objectives of the fire risk research program. A number of issues address specific elements of FRA. The remainder deal with either: a) problem-specific, integrated treatments of fire initiation, equipment damage, and plant response, or b) activities relevant to but not required by the FRA analysis process. Ref. B1 further groups these 42 potential issues into 17 topic areas.

The following table provides the fire risk research program tasks (or other RES program activities) associated with these issues and topic areas. The topics (and the issues within each topic) are presented in order of priority.

### Reference

- B1. N. Siu, J.T. Chen, and E. Chelliah, "Research Needs in Fire Risk Assessment," Proceedings of 25th Water Reactor Safety Information Meeting, Bethesda, MD, October 20-22, 1997.

Priority	Topic Title	Issue	Issue Description	Associated RES Activity [Notes]
1	Circuit failure mode and likelihood	H1	Circuit failure mode and likelihood	Fire risk research program: - Tools for circuit failure mode and likelihood analysis
2	Detection and suppression analysis	S2	Fire protection system reliability/availability	Fire risk research program: - Tools for fire detection and suppression analysis
		S3	Suppression effectiveness (automatic, manual)	Fire risk research program: - Tools for fire detection and suppression analysis
		S4	Effect of compensatory measures on suppression	Fire risk research program: - Tools for fire detection and suppression analysis
		S5	Scenario-specific detection and suppression analysis	Fire risk research program: - Tools for fire detection and suppression analysis - Use of advanced fire models in fire risk assessment
		S1	Adequacy of detection time data	[1]
3	Fire PRA applications issues	O3	Comparison of methodologies	[2,3]
		R5	Multiple unit interactions	Fire risk research program: - Risk significance of multiple unit interactions
		P2	Availability of safe shutdown equipment	IPEEE review
		R4	Seismic/fire interactions	IPEEE review
		R6	Non-power and degraded conditions	[4]
		R9	Flammable gas lines	IPEEE review



Priority	Topic Title	Issue	Issue Description	Associated RES Activity [Notes]
4	Impact of fires on operator performance	P3	Fire scenario cognitive impact	ATHEANA FRA application
		P4	Impact of fire induced environment on operators	ATHEANA FRA application
		P5	Role of fire brigade in plant response	ATHEANA FRA application
		R10	Scenario dynamics	ATHEANA FRA application
4	Risk significance of main control room fires	R1	Main control room fires	ATHEANA FRA application [3,5]
		P1	Circuit interactions	[3,5]
6	Fire initiation analysis	I4	Likelihood of severe fires	Fire risk research program: - Industrial fire experience - Frequency of challenging fires
		I2	Scenario frequencies	Fire risk research program: - IEEE-383 rated cable fire frequency analysis: feasibility study - Industrial fire experience - Frequency and characteristics of switchgear and xfmr fires - Frequency of challenging fires
		I3	Effect of plant operations, including compensatory measures	[3,6]
7	Fire modeling toolbox: assessment & development	E1	Source fire modeling	Fire risk research program: - IEEE-383 rated cable fire frequency analysis: feasibility study - Fire modeling toolbox: input data and assessment - Industrial fire experience - Frequency and characteristics of switchgear and xfmr fires - Frequency of challenging fires - Fire model limitations and application guidance - Use of advanced fire models in fire risk assessment
		E2	Compartment fire modeling	Fire risk research program: - Fire modeling toolbox: input data and assessment - Fire model limitations and application guidance - Use of advanced fire models in fire risk assessment
		H2	Thermal fragilities	Fire risk research program: - Fire modeling toolbox: input data and assessment
		R12	Uncertainty analysis	Fire risk research program: - Integrated model and parameter uncertainty
		H3	Smoke fragilities	Fire risk research program: - Fire modeling toolbox: input data and assessment
		E4	Smoke generation and transport modeling	[7]
		E3	Multi-compartment fire modeling	Fire risk research program: - Fire model limitations and application guidance
		H4	Suppressant-related fragilities	[8]

Priority	Topic Title	Issue	Issue Description	Associated RES Activity [Notes]
7	Risk significance of turbine building fires	R2	Turbine building fires	Fire risk research program: - Risk significance of turbine building fires
9	Experience from major fires	O1	Learning from experience	Fire risk research program: - Experience from major fires - Industrial fire experience
10	Fire barrier qualification and thermal analysis	B2	Barrier performance analysis tools	Fire risk research program: - Fire barrier reliability model development and application
		B3	Barrier qualification	[9]
		B4	Penetration seals	Fire risk research program: - Penetration seals
11	Fire events database	I1	Adequacy of fire events database	[10]
11	Fire barrier reliability analysis	B1	Adequacy of data for active and passive barriers	Fire risk research program: - Fire barrier reliability model development and application
11	Precursor analysis methods	R11	Precursor analysis methods	[11]
11	Fire PRA guidance and standardization	O4	Standardization of methods	[4]
15	International cooperation	O2	Learning from others	See Section 4.6.
16	Risk significance of containment fires	R3	Containment fires	[4]
16	Non-core damage issues in fire risk assessment	R8	Fire-induced non-reactor radiological releases	[4]
		R7	Decommissioning and decontamination	[4]

## Notes

1. Data-based improvements will be difficult, due to the inherent scarcity of data. Model-based approaches to the issue are covered under the task “Use of Advanced Fire Models in Fire Risk Assessment.”
2. This issue should be addressed in IPEEE follow-on activities.
3. This issue will likely be addressed during future fire risk requantification efforts (see Section 6 of the main report), if such efforts are performed.
4. This issue is being addressed in NFPA 805.
5. Analysis of this issue will require input from the task “Tools for Circuit Failure Mode and Likelihood Analysis.”
6. A data-based approach will be difficult, due to the inherent scarcity of data. The results of the task “Frequency of Challenging Fires” should indicate if a model-based approach is feasible.

7. The need for methods, tools, and data will be reassessed following current work investigating the smoke fragility of components, performed under the task "Fire Modeling Toolbox: Input Data and Assessment."
8. Generic Issue 57, "Effects of Fire Protection System Actuation on Safety-Related Equipment" (see NUREG/CR-5580), assesses the risk significance of this issue. This issue is also being addressed in the IPEEEs.
9. Elements of the proposed program discussed in NUREG-1547 (L.Y. Cooper and K.D. Steckler, "Methodology for Developing and Implementing Alternative Temperature-Time Curves for Testing the Fire Resistance of Barriers for Nuclear Power Plant Applications," 1996) are addressed by the tasks "Fire Model Limitations and Application Guidance" and "Use of Advanced Fire Models in Fire Risk Assessment."
10. Nuclear Electric Insurance Limited (NEIL) is currently developing a database for nuclear power plant fire events.
11. Improved accident precursor analysis methods for external events contributors may be addressed under the RES Accident Sequence Precursor program. Discussions of recent work can be found in the following two reports.

R.J. Budnitz, et al, "A Methodology for Analyzing Precursors to Earthquake-Initiated and Fire-Initiated Accident Sequences," NUREG/CR-6544, 1998.

M.B. Sattison, T. Thatcher, and N. Siu, "Accident Sequence Precursor (ASP) Extension Subtasks 1.2 and 1.3 Report, letter report prepared for the U.S. Nuclear Regulatory Commission under JCN W6355, June 1995.